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Original Article

Waste Elimination through Digital Twins: A Pilot Framework for SMEs

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Abstract: *Digital twin technologies have become rapidly growing elements in businesses' pursuits of operational efficiencies, sustainability, and waste reductions. Digital twins are of interest among Small- and Medium-sized Enterprises (SMEs), which often have limited resources and capabilities, and want to adapt their implementation of a digital twin for operational process efficiencies, decision-making improvements, and waste reductions of material inputs and energy. This paper reviews the published literature on the implementation of digital twin frameworks to support SMEs' waste reduction efforts utilizing predictive analytics, real-time monitoring, and closed-loop manufacturing systems. Some of the recent study papers, along with an associated research question from the literature review, contribute to a greater understanding of the possible scaling of digital twins as a technological capability and capacity among SMEs that are supporting improved smart city infrastructure and sustainability initiatives. The images illustrate the benefits of digital twins in a range of industries related to sectors such as manufacturing, logistics, food production, and urban waste. In short, the evidence shows that digital twins provide the capability for organizations to progress from a reactive culture in waste management and harmful practices toward a proactive posture and measurable return on investment and value to the environment. This paper presents an initial framework for starting points, project ideas, and considerations for SMEs considering any digital transformation as a vehicle for waste reduction and significant sustainable development.*

Keywords: *Digital Twins, Waste Elimination, Smes, Predictive Analytics.*

I. INTRODUCTION

Digital twin (DT) technology has emerged in the past decade and has started to permeate various industries across the globe, due to the possibility of new simulation cases, real-time design optimization, and monitoring of real-world processes. A digital twin is a virtual representation of a physical asset, system, or process with real-time data and a predictive model or complex decision tree. DT technology has been increasingly used to improve workplace inefficiencies and waste, for city and industrial applications.

Globally, small and medium-sized enterprises (SMEs) make up a significant portion of industrial output, but many do not manage resources efficiently and effectively, even with modern technologies, partly because of a lack of technology transfer mechanisms. Once digital twin technologies are introduced to SMEs, productivity increases because waste is systematically identified and eliminated, as the future of work opens avenues for reductions in operational costs. This paper discusses options for waste reduction through digital twin technologies in SMEs and references a few contemporary studies on the topic.

II. THE ROLE OF DIGITAL TWINS IN WASTE MANAGEMENT AND OPERATIONAL EFFICIENCY

The waste management using the digital twin method suggests a complicated solution to the type of waste management. Digital twins recreate real-time production systems and services and give operators a chance to understand to what extent it will become malfunctioning or ineffective. This would be under waste management, which implies that the collection vehicles would be timed in an efficient manner, the energy usage would be limited, and the resources would be placed in a strategic location to the regions that hold the best potentials of producing wastes [1]. These benefits can be applied particularly to the SMEs that work on an off-the-lean budget and whose infrastructures are minimal. With the release of digital twin solutions, such enterprises will be able to keep track of the overall microclimate of their work, and they can also be virtualized and introduce cost-effective and efficient solutions.

The third peculiarity of the digital twins is that they may be adapted to the real-time feedback, due to which the closed-loop control mechanism may be introduced, and the optimization of operations at each point may be provided. It is stipulated in the performance appraisal models based on digital twin that incorporates the models that involve Lean Six Sigma. This form of integration is significant to the SMEs that may not particularly need their quality improvement department. The digital twins and the Lean Six Sigma may enable the enterprises to help quantify the key performance indicators (KPIs), find the bottlenecks, and apply the lean solutions to the enterprise in a more accurate fashion [2]. These models enable the SMEs to make fact-based decisions and reduce the cycle times in addition to producing with a high degree of efficiency.

III. ENABLING SMES: ACCESSIBILITY AND CHALLENGES

The potential of the digital twins technologies exists, but the SMEs are not able to use this digital twin because of several barriers. They are very costly to implement, the technical capacity is small, and it does not even offer tailor-made DT solutions, which is why enormous implementation is impossible. However, in the recent past, developments have been in a position to name a few success cases of SMEs that have implemented DT frameworks which are modular and scalable in nature. In such a study, reproduction of what a manufacturing SME was producing, in a digital manner was placed, which resulted in a measurable reduction of the amount of wastage, and a similar answer was equivalent response to the utilization of the equipment [3].

Training and collaboration is the other influencing factor. The partnerships with the academic institutions, technology providers, and industry alliances can be of significant help to SMEs by providing them with advanced data streams as the foundation of digital twin systems. Through this form of partnership, SMEs are able to access DT platforms and tools that are not accessible to them. The knowledge sharing is also crucial to such forms of partnership; this is because in this way, it helps the SMEs to align the adoption of a digital twin to their respective business objectives. It is implemented as Software-as-a-Service (SaaS) solutions, and even the SMEs do not have to think about the infrastructural requirements of creating their digital twin to implement it [3].

IV. DIGITAL TWINS FOR SUSTAINABLE AND CLOSED-LOOP SYSTEMS

The digital twins introduced in SMEs are not only to achieve operational excellence but also to align with the general sustainability goals. The digital twins technologies, in assisting to develop the concept of closed-loop production and waste elimination, can benefit the creation of a paradigm shift in the manner the SMEs use the resources. The transformational opportunity for SMEs that operate in environmentally sensitive domains is the digital twins with the green artificial intelligence (AI). Green AI reduces the power, emission, and management costs of the digital twins [4].

This has particularly been so in the development of a sustainable supply chain. The willingness to use digital twins could be accommodated to help generate closed-loop systems with the assistance of which the waste could be recycled to produce the product, as more recent studies show. The latter would allow the continuous reuse of the materials that could be performed in the case of SMEs whose operations are based on production or logistics, and the scope of environmental influence could be reduced [4]. Furthermore, by digitalizing the whole chain of supply, the business may be engaged in the problem of inefficiencies resolution and ensure that the sustainability goal will be met without the necessity to influence the performance of the operations.

The following Table 1 illustrates a comparison of traditional operational models with digital twin-enhanced systems in SMEs:

Table 1 : Comparative Analysis of Traditional Systems and Digital Twin-Enhanced Systems in SMEs

Parameter	Traditional Systems	Digital Twin-Enhanced Systems
Monitoring Capabilities	Periodic and Manual	Real-Time and Automated
Waste Detection	Reactive	Predictive
Decision-Making	Experience-Based	Data-Driven
Cost of Waste	Often Untracked	Quantified and Minimized
Energy Consumption	Inefficient	Optimized Using AI
Flexibility in Operations	Limited	High Due to Simulation Capabilities
Integration with Sustainability	Low	High with Closed-Loop Feedback

Source: Compiled from references [1], [2], [3], and [4]

V. DIGITAL TWINS IN SMART CITIES AND THE BROADER SME ECOSYSTEM

Along with the internal efficiencies that are generated in an SME, there is the strategic element of the digital twins, which is a part of a larger ecosystem of a smart city. Such projects will contribute to the overall impact of the smart waste projects, as the SMEs will be concentrated in the urban and peri-urban areas in the data-driven municipal waste. The cities are self-sustaining through the assistance of DTs, which blends the SMEs in the information of the sensors, blockchain-based transparency, and AI-based analytics [5]. Due to the concentration of the digital infrastructures, the SMEs in that ecosystem can and do enjoy the benefits of real-time updates, optimization of the waste collection process, and a model of a circular economy.

The problem of digital twins, in particular with distributed ledger technologies, could be viewed as a means of supporting the sustainability of smart cities. The blockchain can also be applied to the achievement of data integrity, and now the interested parties, including the SMEs, can be provided with reliable and clean information regarding waste production, energy consumption, and emissions [5]. These smart city networks will incorporate the SMEs in a way that the policies of the SMEs on waste elimination will be aligned with the sustainability interests of the city, because independent activities will present a higher environmental impact.

The other opportunity that the SMEs stand to take advantage of in the introduction of digital twins in municipal planning is the opportunity to reap the benefits of digital transformation. Digital twins have equally contributed to easing the process, as well as automating it, in certain food-based SMEs such as bakeries. In this instance, the presentation of digital twins of the work of a bakery was able to give the work of the bakery more visibility and evenly redistribute the resources [6]. The online models have the ability to replicate the application of ovens, fridges, and purchase behaviors of the products and allow the SMEs to minimize waste throughout their supply chain. Digital twins ensure that the aberrations are corrected before they can trigger the wastage of materials and energy, and thus are much valued in industries where freshness, time, and quality are central concerns.

The following Figure 1 demonstrates the functional model of a typical digital twin framework tailored for SME waste elimination processes.

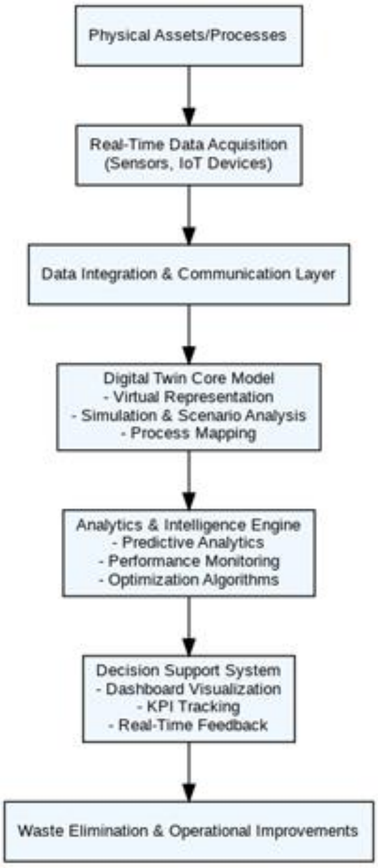

Figure 1 : Functional Digital Twin Architecture for SME Waste Management

Source: Adapted from [1], [3], and [6]

The architecture begins with the collection of real-time data from physical assets, which entails the use of IoT devices and sensors. The information is then passed over to an integration layer that transfers the data to a centralized core of digital twins. It is this core where the virtual demonstration of real processes is provided, and one can simulate situations and study them. Yet, such computerized models are developed with the help of analytics engines or predictive performance monitoring and optimization programs.

The final component is the decision support system, which constitutes the response to the users in terms of dashboards and real-time alerts. The result of this process is that these operations are built to participate in minimizing waste across all functions of SMEs. One can possibly understand why SMEs can utilize digital twins not just for monitoring, but also for strategic changes capable of turning intelligence into a value stream within their operations through the utilization of this architecture.

VI. AI-ENABLED DIGITAL TWINS IN CLOSED-LOOP MANUFACTURING

The second aspect of waste management as stipulated in the framework for SMEs is the implementation of AI and digital twins in constructing closed-loop manufacturing plants. AI-based DTs are able to identify data across the product lifecycle, expose inefficiencies, and provide feedback loops through automatic control of machine settings or processing. In a closed-loop model, the waste obtained during one production process is reused in another process, and therefore the amount of waste requiring disposal is decreased [7].

The process of turning such an ecosystem of manufacturing smarter would not take as much time because the AI algorithms can be trained using previously collected performance data. Proactive maintenance may be carried out, for example, after predictive analytics have identified potential downtimes and associated material losses. To the same effect, intelligent strategizing would imply that the machines would be utilized under optimal terms, thereby saving on power as well as raw material. The general applicability of AI-based digital twins renders them particularly useful for SMEs willing to develop, even though on a smaller scale, and experience a comparable level of improvement in their environmental footprint [7].

The company does not only have strategic market positions focused on the efficiency of closed-loop systems. Business is tenured and consumer-oriented. With the concept of digital twins helping to reduce losses and demonstrate the sustainability of business operations to the public, SMEs would have an opportunity to attract the attention of socially responsible customers and investors. Such functions will not only assist in making the process more cost-effective but also offer a point of differentiation as far as competition is concerned.

VII. PREDICTIVE ANALYTICS AND OPTIMIZATION IN URBAN WASTE COLLECTION

Digital twin infrastructures are at the forefront of the shift in cities from traditional, legacy waste collection approaches to smarter, predictive analytics operations. The application of digital twin technology to manage small- and medium-sized enterprises (SMEs), preferably in the urban environment, or to manage municipal waste management agencies, provides a compelling opportunity to align waste processes and schedules across municipalities or cities. The digital twins represent a simulation of both the physical movements of waste in real life and the future flows of waste—based upon the understanding of past data, seasonality, and consumer behavior [8].

Predictive models supported by a digital twin can leverage information from IoT sensors, enterprise resource planning (ERP) systems, and environmental monitoring to predict when, where, how often, and in what mode randomness should be mapped out to be collected, and what areas should build storage capacity to minimize the risk of overflow in a way that diminishes costs for stores and more effectively plans for hauling it away. In this way, prediction is a means for diminishing waste arising from food production, packaging, and process, while confirming that inspections for health and hygiene, legislative requirements, and social considerations are met, and that practices meet inspection requirements for public health, safety, and sanitary law (at the best times for windows). Location can be coded and integrated to account for human actors in transport change management, if legally and ethically appropriate for risk and admittance. For instance, improving or estimating routing efficiency can be utilized strategically to develop performance-based design routes or to use transport routes that minimize fuel use and emissions (carbon footprint) under any circumstance or as a means to obtain green sustainability goals.

This usage is a clear diversion away from generational legacy best-practice reactive waste management (waste-normalized practices) that SMEs inherit from following legacy dumpster waste practices for a period of decades. Being able to model and analyze a variety of collection and recycling scenarios in a digital environment enables SMEs to take a more proactive stance and be more nimble in fast-changing urban circumstances. Furthermore, as municipalities build ever more digitized infrastructure, SMEs with digital twin platforms will benefit from being able to collaborate and contribute to waste reduction initiatives.

VIII. SUSTAINABILITY-ORIENTED DIGITAL TWINS IN SPECIALIZED INDUSTRIES

Specialized industries (for example, in high-value manufacturing or minerals processing) are beginning to exploit digital twins as enablers of sustainability. For instance, a new digital twin framework has started to be applied to optimize the sustainability of a diamond pilot plant, inclusive of systematically factoring wastage through multimodal resource utilisation pathways [9]. This capability of performing within the frameworks enables evolved digital twins to accurately quantify machine performance, production flow rates for material flows, and associated reduced energy costs with processing pathway outputs, or to maximise the efficiency of lower-cost processing pathways with significantly reduced wastage.

Similarly, and in this industry sector—but particularly relevant for supplier groups such as SMEs—a digital twin incorporating sustainability will be appealing due to its environmental and economic sustainability advantages. Accurate tracking of input materials and recording of outputs from these processes results in contributing less wastage of production factors and assisting with the strict regulatory conditions governing environmental standards. Digital twins can also provide SME operators with visibility into performance by quantifying digitally sampled outputs under different operating conditions. This would add to the operational characteristics of operational practices that are not being measured or observed (as an operational characteristic). In addition to operational characteristics, observations related to digital twins will provide, in the future, an order of discovery for developing energy reduction initiatives. These systems provide near real-time operational transparency and visibility for water use, emissions, chemical inputs, and energy intensity, to be more closely aligned to enterprise environmental management components and technical performance [9].

Historically, these kinds of technologies have primarily benefited larger businesses; however, the digital twin's modularity and scalability characteristics (i.e., for businesses of a more traditional nature) indicate that digital twin solutions might also be viable in SME contexts. If, indeed, SMEs' capabilities to exploit existing models allow them to visualize the same ideas—albeit on a smaller scale—they may still produce business benefits, but without the costs or with a much less laden and sophisticated design or the need to build from scratch. Ultimately, democratizing the thought process behind being a digital twin suggests a state of sustainability and a waste elimination mindset—not simply the way larger businesses do business, but a normalized reality of practice potentially for businesses of various sizes.

IX. TRENDS AND FUTURE DIRECTIONS: DIGITAL TWINS IN LOGISTICS AND SMART INFRASTRUCTURE

Digital twins are among the most generalized applications to logistics and supply chain management. Smaller companies, or those in logistics, distribution, or warehousing, are now using digital twin systems to address inefficiencies usually related to inventory holding, delays in shipments, and positioning of logistics assets. A bibliometric review of studies incorporating digital twins in logistics describes the digital twin as an opportunity for organizations to provide better visibility, reduce waste in transportation, and enhance urban mobility [10].

Small and medium-sized enterprises (SMEs) can utilize DT systems to model logistics processes to identify the optimal route, the best positioning of products, and the best timing to execute their logistics plans. The simulation generates savings in excess fuel consumption and wear and tear on delivery vehicles, while providing the assurance that product quality is maintained during the transport process. The application of DTs also supports delivery-focused logistics by adjusting to traffic, weather, and market conditions concurrently and in real time. For those SMEs with decreasing delivery fleets or decreasing delivery warehouse capacity, DTs provide substantiated reductions in transport and servicing.

Additionally, with the development of smart infrastructures and digital/physical ecosystems, digital twins have firmly established themselves as one of the key technological building blocks for a larger ecosystem of supply network integration. SMEs within the ecosystem will be bound to share data across platforms to facilitate orderly resource allocation and collaboration towards an ecosystem waste reduction pathway for the business or platform. The act of engaging in a closed-loop under a multi-form digital infrastructure demonstrates the ongoing requirement for operational participation in the digital twin program within the emerging sustainable supply network and systems moving forward.

The following figure provides a visual representation of the observed reductions in different types of waste across SMEs after implementing digital twin technologies.

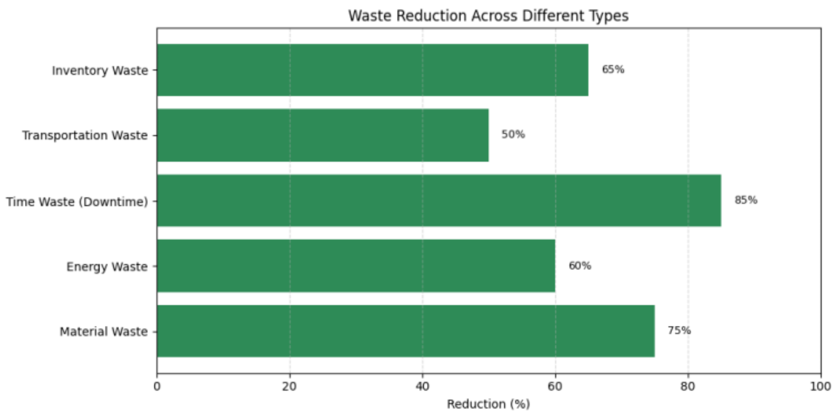

Figure 2 : Waste Reduction Metrics in SMEs after Digital Twin Adoption

Source: Synthesized from [3], [7], [9], and [10]

The most notable outcome was the wasted downtime, which declined by 85% due to superior predictive maintenance in conjunction with real-time tracking of performance. The second waste/value improvement area was in material waste, improving by 75% due to improved resource planning and improved quality control principles. The third waste/benefit area was energy consumption from operations of the facility, decreasing by 60% due to both better optimization of the production process and reduced equipment usage. The next two waste areas were inventory waste and transportation waste, seeing improvements of 65% and 50% respectively, in both instances due to simulating real-time storage management and logistics routing. Overall, this illustrates how effective the digital twin, as a support tool for an SME, can be not only for ease of operations but also as a strategic, operational, double-edged tool for waste improvements and efficiency gains.

X. DIGITAL TWINS FOR OPERATIONAL EXCELLENCE IN SMES

Digital twins benefit not only waste management, but also are one of the first steps toward operational excellence. In this case, and considering that resources are limited and margins are narrow, process optimization is the focus for SMEs to manufacture operational excellence. A digital twin brings process optimization by way of real-time monitoring, predictive diagnostics, and scenario testing, enabling performance improvement through reduced unplanned downtime, increased utilization of assets, and improved corporate/global workflows. Overall, this then assumes improvement to KPIs and KPI components throughout the organization [11].

An additional capability of being able to digitize operational workflows ultimately allows SMEs to make a transition from being largely reactive in nature to being much more proactive. For example, being able to leverage ideas from their digital twin to make predictions on when maintenance should occur will ultimately support reducing costly breakdowns, extending the life of assets, and reducing interruptions to production. The performance measures resulting from the digital twin systems will also enhance employee training by generating feedback loops to promote best practices and improve productivity. Third, the establishment of digital twins will serve as a significant and positive lever for the culture of continuous improvement within an organization by discovering a core factor of competitive advantage [11].

Digital twin systems can naturally scale with the enterprise from day one. As SMEs either add services, add new products, or add levels of production, the digital twins can be recalibrated accordingly. The costs of investment in digital twins will always be a legitimate justification, as well as their scalability with the evolution of enterprise strategy. Additionally, SMEs utilizing digital twins will demonstrate conformance to industry standards, co-author initiatives, and obtain financial resources as a result of the transparency in their operations.

XI. CONCLUSION

The rising adoption of digital twin technologies in various industries is further evidence of progress in waste reduction and optimization. Digital twin systems create an opportunity for data-driven decision-making, predictive analytics, and real-time optimization for small and medium-sized enterprises (SMEs) that have been constrained by cost and/or technology. The employment of digital twin systems in manufacturing, logistics, energy management, and even waste collection of city resources provides yet another example of new practices in which small businesses identify inefficient processes and reduce waste.

Small and medium enterprises (SMEs) are realizing value from modular digital twin frameworks, which integrate AI technology to both reduce waste and enhance the embedding of their work into the larger sustainability agenda. The digital twin framework also has the capacity to reconfigure linear production and consumption systems for ecological resiliency and economic sustainability. Digital twins in smart cities will increase the capacity of SMEs to participate as co-creators of intelligent, low-waste systems.

Digital twin platforms are moving and developing at a rapid pace at this moment. The next step is enhancing interactions, engaging in cross-sector collaboration, and enabling community-wide applications. With the right research, action, development of technology, and policy, digital twin platforms will become key enabling technologies for waste reduction and sustainable innovation for SMEs.

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